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A BRIEF SURVEY OF ADAPTIVE CONTROL SYSTEMS.(U)

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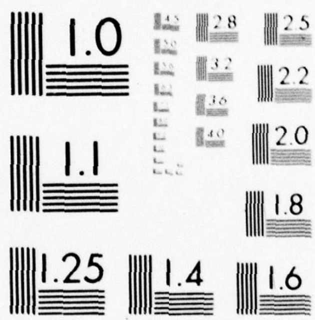

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A BRIEF SURVEY OF ADAPTIVE CONTROL SYSTEMS

Donald A. Stentz

March 1978

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This document summarizes the principles of adaptive control systems and suggests a number of possible uses of this new technology on acoustic tracking ranges. A bibliography of recent literature is included.

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TABLE OF CONTENTS

INTRODUCTION

Historically, targets tracked on acoustic tracking ranges have been accomplished in an artificially quiet environment. All except essential ship movement is stopped, the desired tracking signal is made as strong as possible, arrays are tuned for the desired sound in both frequency and direction, and all transmissions and receptions are kept synchronized.

When it is desired to determine how the target or weapon reacts when operating in a noisy or interfering environment, the above described methods are not satisfactory. For example: If a torpedo is being tested for its tracking and detection ability when being countermeasured intentionally or is being operated in an environment of heavy shipping, the test range should be able to track the torpedo in that environment accurately. If a tracking system could be designed that would ignore all CM, spectral ship noise, and even broadband background noise, much more information about the torpedo characteristics could be obtained. Recent developments, including high density solid state circuitry, may make this a very real possibility. This new technology is called "adaptive control" and by making use of it could result in accurate and highly sensitive adaptive range tracking systems.

The following paragraphs indicate the progress made since about 1966. Parameters used to obtain control in the adaptive process are defined, and the three processes generally used to improve the control characteristics over a reasonable period of time are described.

ADAPTIVE CONTROL SYSTEMS DEFINED

Some systems can be operated in an optimal manner because the controller parameter/s can be preprogrammed to adapt to the system's environment. In order to achieve optimum control, the control parameters are automatically set relative to instantaneous environmental conditions encountered at each point in time. Obviously, the changing environment may be so complicated or unknown that a reasonable model is difficult to estimate and evaluate. When no compromise between the design objectives is possible that will result in an acceptable fixed-parameter system, and where preprogrammed adjustments cannot be made due to a lack of information regarding the system performance with time, the use of an adaptive control system may be indicated [1].

Eveleigh [1] points out that adaptive control provides a possible solution to control problems of the following general form:

> "The system to be controlled is normally exposed to a time-varying environment either in the form of changing system parameters, input signals and disturbances with time-varying statistical characteristics, or changing performance objectives."

Thus an adaptive system is one which measures its performance relative to some performance characteristic called an Index of Performance, or IP, and modifies its parameters to achieve optimum operation.

INDEX OF PERFORMANCE

When designing an adaptive system, it is necessary to establish uniquely the optimum solutions. Eveleigh suggests that the concept of an index of performance, or IP, be utilized and goes on to define some of the more generally accepted IP's.

a. Phase margin (θ_m) - the angle between the negative real axis and the straight line connecting the origin and the point of intersection of the Nyquist plot and the unit circle.

b. Gain margin (G_m) - $1/G_o$, where G_o is the open-loop transfer function magnitude at the frequency when phase lag is 180°. G_m is a direct measure of the ratio by which loop gain may increase before instability occurs. Other factors remain constant of course.

c. Control-loop bandwidth (BW) - this bandwidth may have to be constrained by making use of filters.

d. Peak frequency (M_p) - the maximum magnitude of the closed-loop system transfer function.

e. Percent overshoot - ratio of peak response minus final value to final value.

f. Rise time (T_r) - time axis projection of a line tangent to the response curve at its steepest point.

g. Delay time (T_d) - time it takes the output to rise to half its final value.

h. Settling time (T_s) - time necessary for the output to settle and remain within ± five percent of the final value.

i. <u>Steady-state error</u> (E_s) - for a unit step input this IP is a common constraint and is zero for a type-n system, $n \geq 1$; and it is $(1/K + 1)$ when K is the open loop gain for a type-zero system.

j. <u>Mean-square error</u> - perhaps the most used IP is the mean-square error. It is defined as:

$$E_{ms} = \lim_{T \to \infty} \left[1/2T \int_{-T}^{T} e^2(t)\,dt \right]$$

This IP is generally identified as the (LMS) algorithm. e(t) is the closed-loop control system error.

Each of the above IP's listed have advantages and disadvantages depending on the particular system being adapted and to what extent optimization is to be obtained. Other IP's that will not be defined and should be considered when designing an adaptive system are mentioned below. A complete discussion of these IP's may be found in reference [1].

a. Integral Squared-Error Criterion, ISE

b. Integral of Time Multiplied by Squared-Error, ITSE

c. Integral of Squared-Time Multiplied by Squared-Error, ISTSE

d. Integral of Absolute Value of Error, IAE

e. Integral of Time Multiplied by Absolute Value of Error, ITAE

f. Integral of Exponentially Weighted Squared-Error, IExSE

g. Integral of Modified Exponentially Weighted Squared-Error, IMExSE

A Eveleigh points out, "It is apparent that an 'optimum system" is a very subjective term . . . in one application fast

initial response or rise time for a step input may be all important . . . in other cases rapid response may be equally undesirable . . . the optimum system is highly dependent upon application." When $n > 1$ parameters are available as choice variables, a unique solution is only possible when an IP exhibiting an extreme value at the desired optimum point is used.

If no useful fixed-parameter controller provides acceptable response of the system's operational envelope, then some means must be found for adjusting controller parameters that are sensitive to short-term conditions. If an IP can be selected which dictates the system's instantaneous or short-term average performance quality, and if a control-loop can be designed to optimize the IP automatically by adjusting its parameters, then the new configuration is called an adaptive control loop. This adaptive system is actually an effort to extend the basic optimum-control concept to time-varying systems. It is easily seen then that the optimum parameter value is not generally determined by a single set of measurements, but rather it is approached gradually by a succession of identification, decision, and modification procedures. This suggests that there is a "learning curve" associated with each system as a function of time. The usefulness of a particular system may depend heavily upon the shape of this learning curve; it could, for instance, preclude real time processing.

POSSIBLE USES IN ACOUSTIC TRACKING RANGES

The literature concerning adaptive systems cites many examples for use in missiles, radar antennas, and communications systems. These examples include control of flight pattern, turning a "deaf ear" to noise and interference, tracking, and processing signals in the presence of noise. Very little will be found concerning how this relatively new technology can be used on an acoustic tracking range whether one similar to Dabob Bay or on an at sea range designed for fleet exercises. However, it seems logical that most of the literature concerning the above mentioned uses is directly applicable to the underwater acoustic tracking range. Due to the slowness of sound velocity in water, the speed of some targets, and ranges desired, some adjustments would have to be made. It does seem likely that the basic principles, the IP's, and advantages would apply even though the parameters may vary widely. It is also quite likely that the water environment as a propagation medium, sources of interference, ambient noise level, and other constraints may prove to be a more difficult medium in which to work when compared to the radio frequency case most often described. It would also seem likely that the use of adaptive systems in this more complicated environment may actually make it unnecessary to model the environment over a long time period, but only for the short time required for a single adaptation to be performed. This is related to the learning curve mentioned earlier. A measurement (sample) is taken, and on the basis of that value

or when compared with an earlier sample or the desired signal, a decision is made and the adaptive system parameter/s varied to produce a new point on the optimization or learning curve. We, so to speak, gradually sneak up on the optimum operating point as we learn what is happening from one sample to the next. This is important because it may ultimately relieve some of the hard to achieve requirements of the preprogrammed approach to optimization.

BENEFITS OF ADAPTIVE SYSTEMS

What then are the benefits of using adaptive control on the acoustic tracking range? The most obvious one is to improve the signal-to-noise ratio of the output of the tracking receiver by making the adaptive system ignore noise, multipath, or other interference coming from directions and sources other than that of the desired target. This is to say improve the S/N ratio by decreasing noise and interference. For Dabob Bay, this technique is appealing because by attempting to obtain improvement through stronger signal sources may result in multipath interference, reverberation, and detection of unwanted distant target signals. All this may ultimately leave the S/N ratio unchanged or even reduced. By holding signal power down and effectively decreasing noise power, a beneficial effect can be obtained without the above interference problems arising. It is possible that some improvement could be achieved by adapting the bandwidth of the tracking receiver to the desired signal spectrum while the beam portion is being adapted as well.

ESSENTIAL PROCESSES OF ADAPTIVE CONTROL

Figure 1 shows a block diagram of a system and its adaptive controller. Since the diagram does not identify the system itself, no mention is made of the type of IP used. It could be any of the IP's defined or listed earlier. Of great importance is the sequence of events during a single adaptive event. These are: identification, decision, and modification. Essentially, the controller design depends upon the choice of IP, controller topology, the adjustable parameters of the system, and the characteristics of the means of response. It may be a replica of the desired signal. The output response should eventually match the desired response depending upon the time characteristics of the system's learning curve.

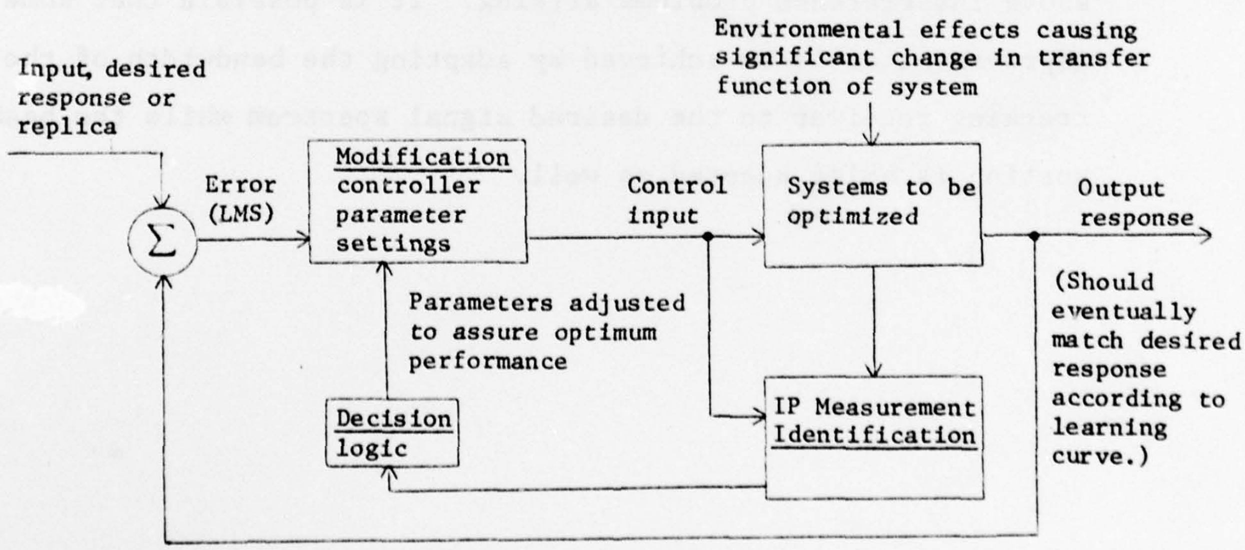

FIGURE 1. CONTROL SYSTEM WITH AN ADAPTIVE CONTROLLER

ADAPTIVE CONTROL LOOP WITH TWO SENSOR INPUTS

From such a block diagram as shown in Figure 1, it is difficult to imagine how it would be used in a given system. Figure 2 shows how the operations could be used to adapt an underwater array composed of two hydrophones so that the array and associated adaptive system would optimize the output. B_1 and B_2 represent beam-steering signals that command the main beam to "look" or steer in a desired direction, θ_s. At the same instant that the beam is steered in the direction desired, an interferring noise occurs in the direction, θ_n. Ordinarily, a side lobe (not shown) would pick up the noise and introduce it into the processor along with the desired signal, thus reducing the S/N ratio. The adaptive process will cause the side lobe in the direction of the noise source to reduce to a null, thus blocking the noise and resulting in a S/N improvement. Again, the three essential processes are indicated: identification, decision, and modification. For each new sensor added to the array, an additional adaptive control loop must be added. It is thus easily seen why solid state circuitry and digital electronics are used rather than the more involved analog technology. If it is assumed that B_1, the input beam steering command for hydrophone 1, is a fixed parameter, this signal weights E_1 in such a manner that in conjunction with the signal from the second hydrophone, E_2, amplifier, hard limiter, correlator mixer and integrator, with added weighting given by B_2 will modify the E_2W_2 value and ultimately optimize the

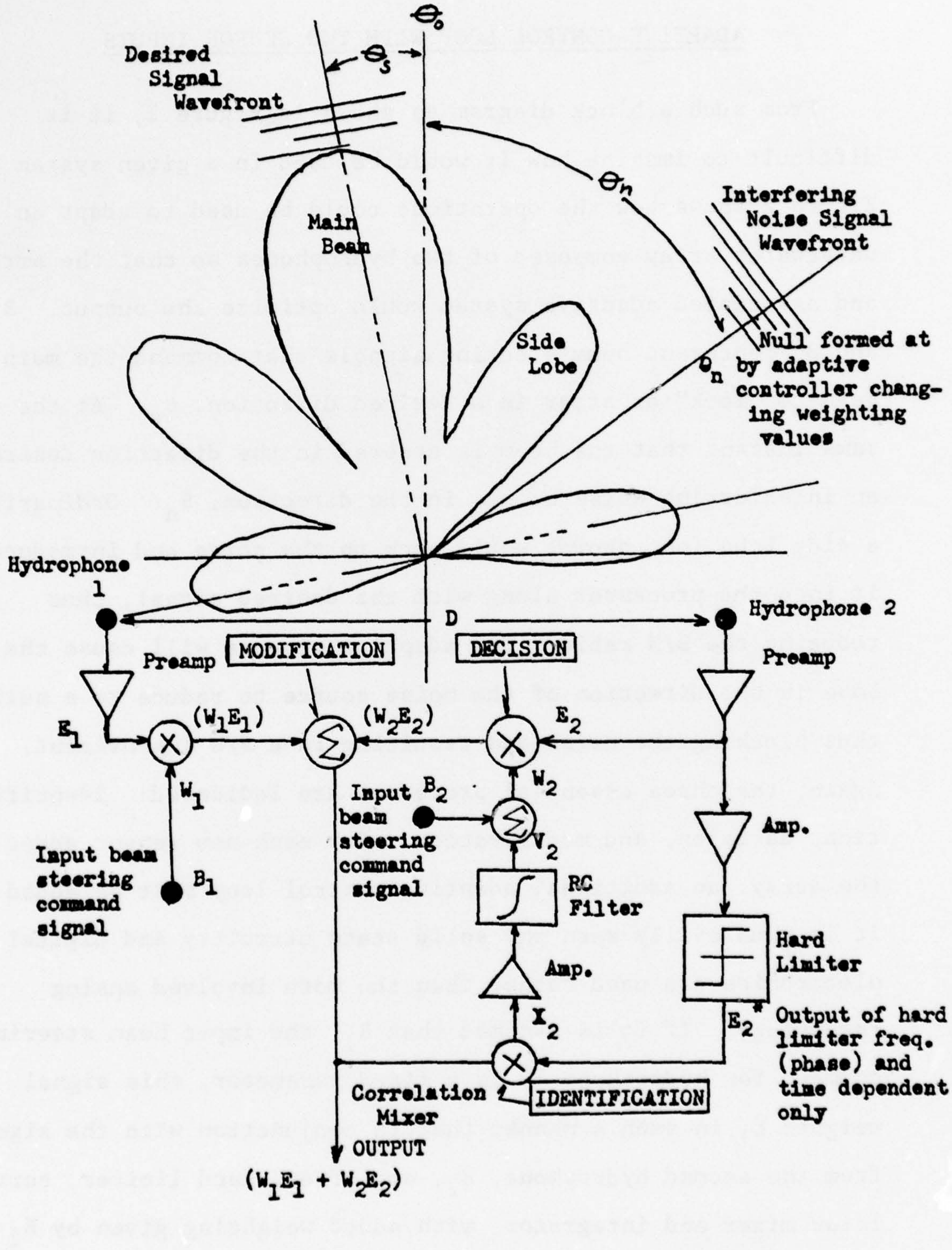

FIGURE 2. TWO SENSOR ADAPTIVE CONTROL SYSTEM

uncorrelated noise or interference signals arriving from the direction θ_n. The same pattern is used if there are signals arriving from more than two hydrophones. Each control loop would eventually be added in the summer just prior to the output. The output would then consist of the sum of the weighted signal from each sensor in the array. The performance factor of ultimate interest in an adaptive array is the improvement in the output SNR as compared to a conventional array subjected to the same interference conditions [2].

RECENT RESEARCH ACCOMPLISHMENTS

Gabriel [2] defines an adaptive array as a system consisting of an array of sensor elements and a real time adaptive receiver processor. When given a beam-steering command, it samples the current environment and automatically proceeds to adjust the element control weights to optimize (determine by the choice of IP) the output SNR in accordance with a selected algorithm. He says that array systems of this type are sometimes referred to as "smart" arrays. This term is appropriate since the adaptive system uses far more of the available information in the array aperture than does a conventional array.

Widrow [3], [6] describes an adaptive noise canceller configured as a notch filter and realized by an adaptive noise canceller. Advantages of this method are that it offers easy control of bandwidth, an infinite null, and the capability of adaptively tracking the exact frequency of the interference. This appears to be of value for tracking ranges as it sometimes becomes necessary to track "keep track of" the unwanted source of the interference in addition to reducing its effect on the desired signal. For example: If a countermeasure is attached to a vehicle, and a null is formed in the direction of the CM, then it would not be possible to track signals from the CM vehicle--tracking the null would provide the necessary information about the activities of the CM vehicle while the CM is nulled in the array aperture. Widrow points out various applications for using this principle of adaptive noise cancelling among which

he includes noise in speech signals, antenna side lobe interference, and periodic or broadband interference for which there is no external reference source. Adaptive noise cancelling is a method of optimal filtering that can be applied whenever a suitable reference input is available. Widrow and his coworkers established the least mean square (LMS) algorithm based on the method of steepest decent. Griffiths [5].

The sensitivity of an array of sensors to interfering noise sources can be applied whenever a suitable processing scheme of the outputs of the individual array elements can be found [4]. The particular combination of array and processing performs as a filter in both space and frequency. Using the LMS criterion, Widrow shows the sharpening of the null in the direction of the noise source as each sample is taken and the learning curve is forced toward the optimum condition. Tracking a particular target from among multiple targets seems quite possible when using adaptive technology. The tracking array positively listens for the desired target and determines through time of arrival by taking into consideration the environmental condition and the last or predicted position of the target.

CONCLUSIONS

This report has described the adaptive control system by defining the most commonly used Index of Performances, IP's, and discussing the three essential processes, identification, decision, and modification, that are involved in all such systems. A block diagram of a system composed of two sensors is included. A number of possible applications of adaptive systems that could find use on an acoustic tracking range are discussed. One of the purposes of this report was to acquaint the reader with the research being carried on in the field of adaptive control systems. To help provide a measure of this activity, several reference lists are included.

It seems quite possible that many of the possible approaches of adaptive processing may be applicable to the acoustic tracking range. These would include tracking improvement, keeping track of noise and interference sources, reduction of signal strength thereby reducing multipath and reverberation problems, communications, and various other signal processing applications associated with the range operation.

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